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USSR Report

SPACE

(FOUO 10/80)

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SPACE APPLICATIONS

UDC 528.06(26):629.78

PROCESSING SATELLITE DATA FOR THE DETERMINATION OF THE COORDINATES OF A MOVING STATION

Moscow GEODEZIYA I KARTOGRAFIYA in Russian No 7, 1980 pp 23-27

/Article by Yu.G. Firsov and B.D. Yarovoy/

/Text/ For the solution of special navigational problems related to the support of marine geodesic and geophysical work that is being performed on moving surveying ships that are beyond the effective range of highly accurate land-based radiogeodesic systems, at the present time the utilization of data from a Doppler satellite navigation system (SNS) offers the most promise.

The information that is obtained is processed by an on-board computer. The accuracy of the determination of a moving station's coordinates depends to a considerable degree on the satellite data processing algorithm that is used. The problem of determining an object's location on the basis of data from navigation satellites can be solved in different coordinate systems. The choice of the system is basically determined by the specific nature of the problem to be solved and the number of computations involved. The unique feature of the integral Doppler method is that when a surveying ship is in communication with a satellite it is, as a rule, in motion; consequently, its coordinates can be calculated for only a single passage of the satellite. In connection with this, the measurements that are made are inadequate for determining all three coordinates with the same degree of accuracy. For this reason a spherical geocentric system of coordinates is used in Doppler navigation, and the least accurately determined coordinate is the station's geocentric distance, which is considered to be a known value during the processing /3/.

The most widely used model for the solution of the problem described above is equalizing the completed measurements relative to three unknowns: two geocentric coordinates and the base frequency. Prior information about the accuracy of the base frequency's determination is not taken into consideration, which is the same as acknowledging it to be a completely unknown value. In turn, the northerly (V_N) and easterly (V_E) components of the velocity vector and the ship's radius vector (R) are considered to be errorfree initial data. In accordance with this, we obtain a system of n-parametric correction-factor equations /1,3/:

$$c\delta F + a_i\delta\varphi + b_i\delta\omega - \Delta l_i = v_i;\ P_i = \frac{\mu^2}{m_i^2},\quad i = 1, 2, \ldots n, \tag{1}$$

where a_i, b_i, c = coefficients of the parametric correction-factor equations; Δl_i = free term of a parametric correction-factor equation; δF, $\delta\varphi$, $\delta\omega = \delta\lambda \cdot \cos\varphi$ are the correction factors of the values being determined (base frequency and geocentric latitude and longitude); v_i = correction factor for the measured difference in distances; P_i = weight of a parametric correction-factor equation; m_i = mean-square error in determining the difference in distances by the integral Doppler method; μ = mean-square error of a unit of weight.

The solution of system (1) by the method of least squares makes it possible to determine the most probable coordinates at the final moment t_k of a chosen k-th integration interval and the value of the base frequency during the realization of the integral Doppler measurements.

As practice in using SNS's, special experiments, and theoretical research have shown, the accuracy of the determination of a moving station's coordinates is basically limited by the accuracy with which systematic errors are eliminated from the elements of the computation. Therefore, the accuracy of satellite navigation depends essentially in the type and accuracy characteristics of the facilities used to compute the ship's path. This fact means that there are certain difficulties involved in using an SNS on a moving ship, since the required accuracy in determining the computation elements cannot always be achieved under seagoing conditions.

In most published works devoted to investigating the accuracy of the determination of an object's coordinates with an SNS, the accuracy of the elimination of the systematic errors is not taken into consideration. For example, in /2/ the errors in the coordinates are computed on the basis of random measurement errors, while the effect of the systematic errors is expressed as a displacement of the site's coordinates that is proportional to the magnitude of the possible systematic error. The author of this work presents graphs that illustrate, on the one hand, the radial mean-square error in the determination of the coordinates, caused by the effect of random errors in the measurements, as a function of the satellite's traversing angular height, and on the other, the magnitude of the coordinates' displacement as a function of the traversing angular height and the specific values of the systematic errors (the geocentric radius of the ship's vector or the velocity vector's components). Such information can obviously be used for an approximate operational estimate, but it is not very useful for supporting marine surveying work, which requires a complete and comprehensive evaluation of the quality of the obtained coordinates, with due consideration for the specific conditions and special features of each individual determination. The required evaluation of the accuracy can be realized only on the basis of equalizing the measurements with due consideration for the accuracy of the determination of the systematic errors that are intrinsic to the integral Doppler method of determining a site's coordinates under marine conditions.

When an SNS is used, the errors in the velocity and base frequency components (assuming the use of two-frequency measurements of the Doppler shift) should be regarded as the basic systematic errors of navigational parameters that are obtained at different times on the basis of integral Doppler measurements and reduced to a single location. In connection with this, on the one hand it is necessary to consider the correction factors that eliminate given systematic errors as measured, while on the other hand, it is necessary to regard them as values determined simultaneously with the ship's coordinates. From this (using the previously adopted definitions), the system of parametric correction-factor equations takes on the form [4]

$$\left.\begin{array}{c} c\delta F+(t_k-t_i)a_i\delta V_N+(t_k-t_i)b_i\delta V_E+a_i\delta\varphi+b\delta\omega-\Delta l_i=v_i; \\ \delta F=v_F; \\ \delta V_N=v_{V_N}; \\ \delta v_E=v_{V_E}; \\ i=1,\ 2,\ \dots\ n \end{array}\right\} \qquad (2)$$

where δV_N, δV_E = correction factors for the computed values of the components of the ship's velocity; t_i = moment of termination of the i-th integration interval.

In view of the independence of the measurements' components, the weighting matrix is quasidiagonal and will be

$$P=\mu^2\left\|\begin{array}{cccc} m_1^2\dots 0 & & & \\ \cdot\ \cdot\ \cdot\ \cdot & & 0 & \\ 0\dots m_n^2 & & & \\ & m_F^2 & & \\ & & m^2v_N & K_{V_NV_E} \\ 0 & & K_{V_EV_N} & m^2v_E \end{array}\right\|^{-1}, \qquad (3)$$

where m_F = mean-square error of the base frequency; m_{V_N}, m_{V_E} = mean-square error of the components of the ship's velocity.

The assumption of relatively equal accuracy that is used for the practical realization of the algorithm will simplify the solution considerably. In connection with this, it is convenient to assume that the mean-square error for a unit of weight equals the mean-square error of the difference in distances ($\mu = m_i$), as a result of which the mathematical transformation is simplified.

After solving system (2) with weighting matrix (3) by the method of least squares, we obtain more precisely defined values of the base frequency and the components of the ship's velocity, as well as the most probable coordinates at moment t_k by which the measurements were made. At the same time,

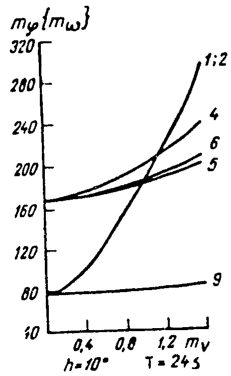
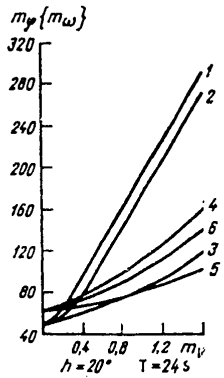


Figure 1.



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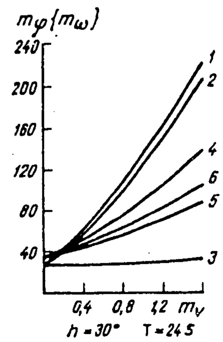

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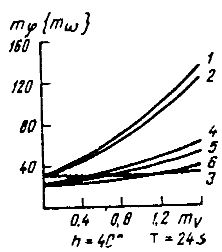

Figure 4.

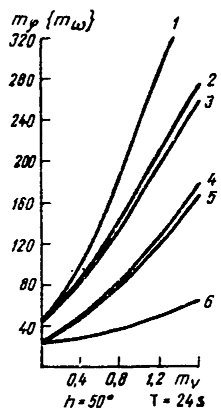

Figure 5.

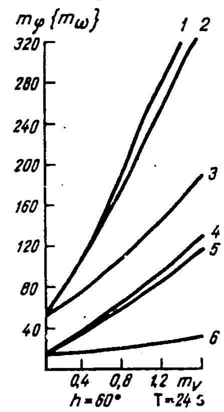

Figure 6.

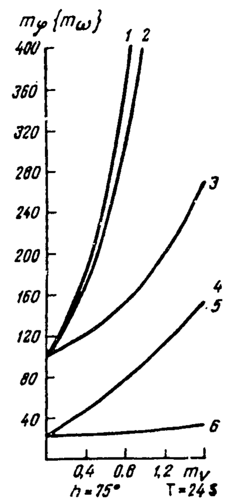

Figure 7.

it is also possible to obtain a combined correlation matrix of the values being determined.

In order to investigate the effect of errors in the velocity components on the results of satellite determinations of a ship's path, we used a navigation satellite program that included a full complex of integral Doppler measurement processing, beginning with decoding of the information received from satellites of the "Tranzit" series and subsequent equalization of the data in accordance with the proposed algorithm. The evaluation of the accuracy of determinations with different course configurations, as characterized by the satellite's traversing angular altitude (h), was made on the basis of the coordinate correlation matrix K_X, as derived from the equalizing equations:

$$K_X = \left\| \begin{matrix} m^2_\varphi K_{\varphi\omega} \\ K_{\omega\varphi} m^2_\omega \end{matrix} \right\|. \tag{4}$$

The computations were made according to the program, using Doppler measurements with an integration interval T-24 s, for different satellite traversing angular heights and a range of measurement of the mean-square errors in the velocity components of 0-1.6 knots.

On the basis of the results that were obtained, graphs (Figures 1-7) of the following functions were constructed:

$$\left.\begin{aligned} m_\omega &= f_1(h,\ m_{V_N},\ m_{V_E}); \\ m_\omega &= f_2(h,\ m_{V_N},\ m_{V_E}=0); \\ m_\omega &= f_3(h,\ m_{V_N}=0,\ m_{V_E}); \\ m_\varphi &= f_4(h,\ m_{V_N},\ m_{V_E}); \\ m_\varphi &= f_5(h,\ m_{V_N},\ m_{V_E}=0); \\ m_\varphi &= f_6(h,\ m_{V_N}=0,\ m_{V_E}). \end{aligned}\right\} \tag{5}$$

In the equalizing equations we used the value $\mu = 5$, which corresponds to the average conditions of two-frequency integral Doppler measurements.

The graphs are used to read the values of the mean-square error (in meters) of the coordinate being evaluated that corresponds to the available accuracy of the measurement of the velocity components of the ship's course (in knots), for specific values of the traversing angular altitudes of a satellite's passage.

These graphs make it possible to evaluate the nature of the effect of errors in computation (of the velocity components) on the accuracy of coordinate determination for defined geometric conditions of satellite passages. In particular, the results that were obtained make it possible to refute the widely held opinion that there is a predominant error in longitude for any geometric conditions of location. It was ascertained that for $h < 15\text{-}20^\circ$, the ellipse of errors is elongated along the meridian, in the interval $20^\circ < h < 30^\circ$ it is almost a circle, and as the traversing angular altitudes increase it becomes elongated along the parallel; in the extreme case ($h = 90^\circ$), it becomes a band with an undetermined value for the site's longitude. When there are errors in the velocity components, the nature of the distribution of the errors in the coordinates changes substantially.

These principles for evaluating the accuracy of the coordinates of a survey ship, as obtained with the use of a satellite navigation system for a moving ship, have been used as the basis of an improved data processing algorightm that makes it possible to allow for the accuracy of the measurement of the velocity vector's components under specific seagoing conditions.

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USE OF SPACE PHOTOGEOLOGICAL MAPS IN THE PREDICTION OF ORE REGIONS

Moscow ISSLEDOVANIYE ZEMLI IZ KOSMOSA in Russian No 2, 1980 pp 34-43

[Article by M. A. Beloborodov and V. S. Kogen, All-Union Aerogeological Scientific-Production Combine "Aerogeologiya," Moscow]

[Text] At the present time space photographs of the earth are finding broad application in the mapping of individual structures, more precise determination of the geological structure of the territory and in regional space photogeological mapping of extensive areas. The purpose of space photogeological mapping is the compilation of geological maps on the basis of a joint interpretation of the results of interpretation, and also geological, geophysical and geomorphological data obtained by an analysis of existing maps and with additional ground study of the interpreted features. In the future space photogeological maps may be used in space photomineragenetic, predictive and other investigations. The marked increase in the volume of information used in these cases for the prediction of minerals is giving special timeliness to the matter of complex interpretation and synthesis of different kinds of information [1]. This article is devoted to the possibilities of predicting ore regions on the basis of joint use of space photogeological maps and geological-geophysical data.

As is well known, the peculiarities of space photographs applicable to the purposes of geological mapping are: great coverage; natural generalization of areas; comparability of the videoinformation received under equal conditions for separated regions; selectivity of videoinformation and its nonequal detail (in geological respects). This affords a possibility for carrying out geological investigations by the deductive method, indirect study of the deep structure reflected in the landscape and terrain photoimage and clarification of earlier unknown geological features and their associations.

The selectivity of the geological information reflected on space photographs is governed by the different photogenetic properties of the geological formations, which are related to the physicochemical properties of the rocks, their bedding conditions and the physiographic position of the photographed feature. Thus, space photographs have a definite "geological resolution," only partially related to the resolution of the photomaterials in the geometric sense of this term.

These properties of space photographs were used in the compilation of medium-scale space photogeological maps of different regions in Siberia and the Far East [2, 3]. The following principles were established as the basis for space photogeological mapping:

1. Small-scale and then medium-scale photographs are first subjected to study. On all photographs the analysis and interpretation are carried out from the largest to the smallest features. A result of application of this principle is the naturalness in the outlines of the geological features revealed on space photographs and reflected on a space photogeological map.

2. The interpreted space photofeatures are subjected to multisided photointerpretation -- geological, geophysical and geomorphological. A result is an increase in the reliability and completeness of the interpretation of space photofeatures and a decrease in the number of elements not subject to geological interpretation, that is, an increase in the resolution of the space photogeological map as a whole.

3. The basis for interpretation is the principle of universality of geological, geophysical, geomorphological and videoinformation indicators, governed by their genetic similarity and interrelationship. This determines the possibility of use of different characteristics as indicators of the surmised geological feature and also the possibility for applying formal methods for multisided interpretation and prediction. As a result, the criterion for geological reality of a space photofeature is the presence of geological and (or) geophysical, morphostructural and other elements conformal to it.

4. A space photogeological map reflects only those geological features which are interpreted on space photographs. In accordance with the above-mentioned properties of space photographs a result of such dominance of videoinformation is a nonequal detail of dissection of stratified strata, intrusive and volcanic complexes, metamorphic formations, etc. in different tectonic and landscape-climatic regions.

5. A space photogeological map has a structural-lithological orientation, which is attributable, first of all, to the fact that among the geological factors exerting an influence on the landscape the most important are the physicochemical properties of the rocks and their bedding conditions, and second, to the fact that such a nature of the geological interpretation of space photofeatures is preferable in subsequent tectonic or mineragenetic investigations. The result is a map representation of structural-mineralogical complexes which are characterized by a specific photoimage, composition, bedding conditions and tectonic position, which in general corresponds to the concept of a space photogeological complex.

The content of space photogeological maps and the general sequence of investigations applicable to the problems of space photogeological mapping have been considered before [2]. Experience in space photogeological mapping has indicated the broad possibilities of the detection of various types of geological and morphological features on the photographs. These include extended linear, sinuous, arcuate and annular tectonic zones, intrusive and stratigraphic contacts; granite-gneiss and metamorphic domes; intrusive masses and volcanic structures; aureoles of hornfels and secondary quartzites; buried geological bodies or those not exposed by erosion, etc. In some cases the totality of such features, detected for the first time, substantially changes the structural pattern of the territory, the outlines of major tectonic regions, the nature of their boundaries and internal structure, making possible a new approach to an understanding of the history of their formation. Various kinds of minerals are spatially associated with many of the features detected on the space photographs, including earlier unknown faults and annular structures. A comparison of space photogeological maps with mineral maps indicates the presence of statistically stable spatial relationships of definite types of mineralization and space photofeatures of different genesis. This creates favorable prerequisites for the prediction and search for minerals on the basis of space photogeological information.

In the formulation of such investigations in one of the regions of the Far East the following goals were set: evaluation of the effectiveness of space photogeological methods in the prediction of minerals; carrying out of a purposeful synthesis of videoinformation, geological and geophysical characteristics of the territory for prediction purposes.

The solution of these problems required adoption of a criterion of the effectiveness of use of different kinds of information. As such a criterion it is possible to use the magnitude of the contribution of the used information to the final result, that is, to the separation of the territory into sectors, obtaining different evaluations with respect to its prospects with respect to mineralization. The following indices were adopted for an evaluation of effectiveness:

a) the value of the informational significance of the data used in prediction (in the case of a high effectiveness it is maximum);
b) the fraction of the area whose evaluation at a stipulated reliability level remains uncertain (with a high effectiveness it is minimum);
c) the degree of localization of the most promising sectors (in the case of a high effectiveness such sectors must occupy a minimum area).

There must be a universal quantitative index for comparison and synthesis of different kinds of information. The application of such an index in an evaluation of the similarity of investigated features with known ore-bearing areas ensures effectiveness of the analogue method. Such a unique measure, making possible a comparison and synthesis of different kinds of information with allowance for their individual significance, is the information content of the criteria for the features to be predicted. By the term "information content of criteria" is meant the measure of the spatial relationship between their values and the location of features of the predicted class (in particular, ore regions).

Each criterion (for example, age of rocks, density of fissuring, magnetic field strength, etc.) can be characterized by two indices: a) a number of special information contents of their individual values (gradations); b) mean integral information content (informational significance). The special information content of gradations of a criterion characterizes the relationship between a particular gradation and the predicted feature and takes into account the frequency of occurrence of the gradation beyond the limits of the features. This index makes it possible to sum different kinds of information, formulate an idealized (optimum) model of the feature and construct a predictive map in dependence on the specific values of each criterion. The informational significance of a criterion is a characteristic which simultaneously takes into account the special information contents of the gradations of a particular criterion and the frequency of their occurrence for the predicted features. The optimum combination of information content and the frequency of occurrence gives the maximum informational significance

Table 1

Information Content of Criteria for Predictable Ore-Bearing Features

No	Criterion	Information content of criterion, arbitrary units	Number of gradations	Most favorable gradations	Information content of gradation, arbitrary units
1	Genetic type of closest annular structure	15	9	Plutonic-volcanic type of annular structure	20
2	Facies of metamorphism of ore-bearing rocks	9.3	9	Epidote-amphibolite facies	12
3	Morphology of annular structure	7.9	5	Concentric-annular structure	10
4	Thickness of ore-bearing stratum	7.3	6	Thickness of ore-bearing stratum greater than 5 km	9
5	Key stage in the development of the earth's crust for particular area	4.3	10	Geosynclinal stage in development and stage of Mesozoic activation	4.5
6	Strength of averaged magnetic field	3.6	7	Less than 110 gammas	11
7	Age of ore-bearing rocks	3.4	9	Upper Proterozoic	8.4
8	Character of dislocations	3.1	8	Folded-block	3.5
9	Composition of rocks	3.1	7	Silicate-alumosilicate	2.6
10	Diameter of annular structure	2.9	4	Diameter 20-50 km	4.2
11	Genesis of ore-bearing rocks	2.6	9	Sedimentary terrigenous	3.2
12	Presence of neotectonic depressions of different types	2.2	9	Not detected (not characteristic)	2.3

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Table 1 (continued)

No	Criterion	Information content of criterion, arbitrary units	Number of gradations	Most favorable gradations	Information content of gradation, arbitrary units
13	Presence of Mesozoic volcanites, their distance	2.1	5	Mesozoic volcanic formations at distance of about 5 km	2.3
14	Nature of photopattern on space photograph	1.9	10	Thin-banded photopattern	4.0
15	Direction of minimum change in averaged magnetic field	1.7	9	Azimuth 110-130°	3.1
16	Direction of minimum change in field of residual gravity anomalies	1.7	9	Azimuth 70-150°	3.1
17	Predominant orientation of fissures interpreted on space photographs	1.5	9	Sublatitudinal and its combination with submeridional	6.2
18	Difference in angles of minimum changes in gravity and magnetic fields	1.4	10	0°	1.8
19	Outlines of photofield in limits of ore-bearing area (on space photo)	1.2	3	Photofield has an elongated configuration with a ratio of width to length 1:5	3.2
20	Characteristics of morphology of structures holding mineralization	1.2	8	Synclinal structures	3.2
21	Degree of anisotropicity of magnetic field	1.2	8	10-50	2.9

Table 1 (continued)

No	Criterion	Information content of criterion, arbitrary units	Number of gradations	Most favorable gradations	Information content of gradation, arbitrary units
22	Geological formations associated with interpreted fissures	1.2	9	Hydrothermal changes in the type of beresites-listvenites	2.6
23	Characteristics of stereophotopattern	1.1	10	Radial-annular stereophotopattern	1.9
24	Density of photofield on space photo	1.0	10	Slightly increased	1.9
25	Distance to nearest lineament of gravity and (or) magnetic field	1.0	5	Up to 5 km	1.7
26	Orientation of tectonic zones relative to folded structures	1.0	4	Diagonal	2.0
27	Degree of anisotropicity of gravity field	0.9	8	10-50	2.6
28	Contrast of photoimage on space photograph	0.9	10	Moderate	2.0
29	Distance from large intrusions of Mesozoic granitoids	0.8	5	At distance of more than 5 km	1.0
30	General geotectonic position	0.8	5	Myogeosyncline	1.0
31	Saksov-Nigard residual anomalies	0.8	10	0.25-0.48	2.6

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Table 1 (continued)

No	Criterion	Information content of criterion, arbitrary units	Number of gradations	Most favorable gradations	Information content of gradation, arbitrary units
32	Position of ore-bearing area relative to annular structure	0.7	5	Beyond limits of annular structure (along periphery)	1.0
33	Combination of field of residual gravity and magnetic field anomalies	0.7	23	Field of residual anomalies: -30-0 mgal, magnetic field: -200-0 gammas	3.2
34	Direction of minimum change in regional gravity field	0.7	9	Azimuth 110-130°	1.8
35	Number of main geological complexes in limits of area	0.6	7	Maximum (7 or more)	14.0
36	Degree of anisotropicity of regional gravity field	0.6	8	5000-10 000	1.3
37	Gravity field gradient	0.5	7	1.8-2.2 mgal/km	4.0
38	Entropy of gravity field	0.4	8	-4.26- -3.62	0.6
39	Distance to nearest tectonic zone interpreted on space photograph	0.3	5	From 15 to 25 km	1.1
40	Gradient of regional gravity field	0.3	6	0.48-0.65 mgal/km	1.2
41	Presence of unexposed geological bodies and their composition (from space photogeological mapping data)	0.3	5	Presence of unexposed granitoid bodies (granite-gneisses?)	3.2

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Table 1 (continued)

No	Criterion	Information content of criterion, arbitrary units	Number of gradations	Most favorable gradations	Information content of gradation, arbitrary units
42	Gradient of averaged magnetic field	0.2	9	4.6-6.8 gammas/km	1.6
43	Residual gravity anomalies	0.2	9	4-11 mgal	0.8
44	Standard deviation of magnetic field	0.1	7	Less than 50 gammas	0.1
45	Density of interpreted tectonic zones	0.1	6	Two zones, each 400 km^2	0.2
46	Total area of rock outcropping, including ore-bearing areas	0.1	7	Several thousand km^2	0.2
47	Density of fissures interpreted on space photo	0.06	4	3-4 per 100 km^2	0.1
48	Vein intrusive formations	0.05	9	Fields of development of Mesozoic dikes	0.3
49	Total area of photofield, taking in ore-bearing area	0.04	3	Several tens of thousands km^2	1.7

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of the criterion. This index makes it possible to detect criteria whose study can give the maximum effect and determine the optimum sequence for their study. For example, in accordance with the informational significance of different criteria a possibility appears in prediction to investigate first of all the annular structures, rejecting features of a definite genesis and size and then near the annular structures detect sectors of development of Precambrian greenstones, etc.

The method for predictive-mineragenetic investigations on the basis of a space photogeological map was developed in the example of an evaluation of the prospects for locating ores in one of the regions of the Far East with an area of about 160,000 km^2. In accordance with the scale of the initial space photogeological maps, geological and geophysical maps the object of prediction is an ore region whose area according to empirical data varies in the range 100-400 km^2.

The "Otsenka" ["Evaluation"] algorithm has been developed and used for solution of the formulated problems [1]; it makes use of the analogue method, in essence the only geological prediction method. The problem is reduced to an evaluation of the similarity measure (for the totality of the criteria) for the investigated area and an earlier studied area where ore deposits have been determined. The essence of the "Otsenka" algorithm, like other algorithms for prediction by image recognition methods, is the obtaining of some function whose arguments are the values of the criteria at points in the investigated area. This function must assume the most different values with the substitution of arguments corresponding to features of different classes. The values assumed by such a function are a criterion for the classification of features. The algorithm is applied in the "Otsenka" program using a YeS-1022 electronic computer. The program makes it possible to evaluate the information content of gradations of criteria, formulate an optimum model of an ore region, evaluate the informational significance of the criteria and measure of similarity between the investigated sector and standard references entered into the electronic computer. Thus, the similarity measure appears in the role of a classification criterion for a complex of criteria taken into account and is an index of the prospects of the territory (without allowance for economic geography, mining geology and technological conditions).

The investigated territory was divided into equal-area elementary grid squares, individual objects for prediction whose area was determined by the detail of the prediction and the initial data. In subsequent procedures they are approximated by points, to which all the information is related. The initial information was taken from medium-scale geological and space photogeological maps, space photo interpretation sheets, magnetic and gravimetric maps. A total of 49 criteria were used, including 16 geological, 17 space photogeological and 16 geophysical. We will note the two principal conditions for selecting criteria: a) they must be described for the entire investigated territory, b) the initial set of criteria includes their maximum number; it is undesirable to dispense with those which seem to be of little significance because the problem includes evaluation of significance; criteria with a low information content are excluded automatically by the algorithm in the course of solution of the problem.

In computing the similarity measure use is made of the sum of "weights" of the criteria and therefore provision is made for an analysis of dependent criteria, the choice from their number of those which have the maximum informational significance, and exclusion of the remainder. A list of criteria is given in Table 1. We note that no use was made of known direct mineralization criteria (ore shows, concentrate aureoles, etc.), closely associated with different degrees of study of individual parts of the territory and frequently also with geomorphological conditions. In describing the criteria use was made of nominal, serial and metric scales, depending on their meaningful sense. In particular, a nominal scale is used in characterizing the composition of the rocks, a serial scale is employed in characterizing their age and a metric scale is used in characterizing their physical fields. The gradations of the criteria are determined in accordance with these scales: for rock composition -- 1 -- silicate, 2 -- alumosilicate, 3 -- calcareous, etc.; for the age of rocks -- 1 -- Cenozoic, 2 -- Mesozoic, 3 -- Upper Paleozoic, etc.; for physical fields -- the real digital values.

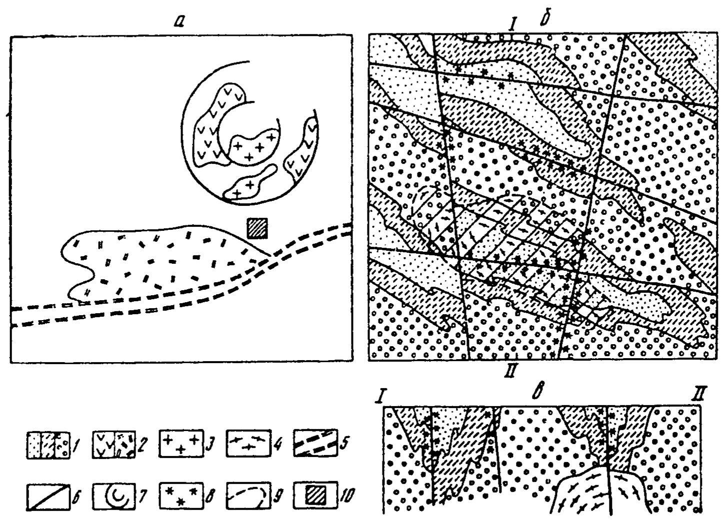

Fig. 1. Optimum model of predicted ore region (a -- geological position of region; b) optimum geological structure of region; c) geological section along line I-II); 1) Upper Proterozoic sedimentary greenstone-modified strata of geosynclinal complex; 2) Mesozoic volcanic formations; 3) Mesozoic granitoids; 4) Archean and Early Paleozoic granite-gneisses; 5) major tectonic zones; 6) dislocations; 7) polylinear annular structure of plutonic-volcanic genesis; 8) hydrothermally modified rocks; 9) outline of unexposed mass of granite-gneisses; 10) predicted ore region

In formulating a decision rule for the classification and evaluation of the quality of the results use was made of 43 standard features -- ore regions, of which 33 were features incorporated into the electronic computer and 10 were controls. The following basic data were introduced into the electronic computer: 1) characteristics of the territory at points approximating individual objects of prediction; 2) gradations of those criteria which are described by nominal or serial scales; 3) coordinates of the control and reference features, as well as those sectors for which prediction is irrational as a result of lack of the necessary information or due to their tectonic position.

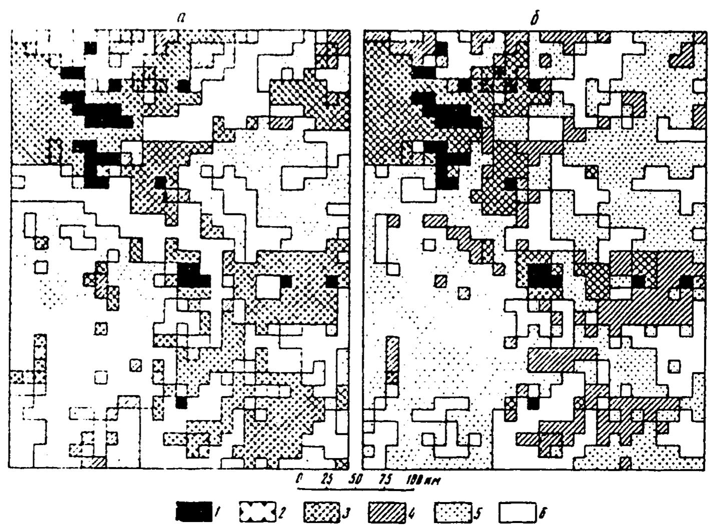

Fig. 2. Fragments of maps from computer evaluation of prospects of finding minerals: a) using criteria taken from geological map; b) using criteria taken from geological and space photogeological maps): 1) reference features [standards] (ore regions with industrial deposits); 3-6) similarity measure for investigated sectors with reference features; 3) more than 0.75; 4) from 0.55 to 0.75; 5) from 0.25 to 0.55; 6) less than 0.25.

It must be emphasized that we did not introduce and did not use at all any preliminary subjective evaluations of criteria (expert evaluations, units, etc.). The operations were carried out only with discrete descriptions of the territory and the coordinates of the reference features. The subjectivity of the evaluation is determined by the reliability of the data (maps) used, the choice of criteria and the nature of the gradations of those criteria which are described by nominal or serial scales.

These investigations made it possible to: 1) carry out ranking of criteria on the basis of informational significance and maximum information content of their gradations (Table 1); 2) give a comparative evaluation of the effectiveness of use of space photogeological maps, geological and geophysical information for evaluating the prospects of a territory (Tables 2, 3); 3) formulate an optimum model of the predicted ore region in which the most important prerequisites for the localization of mineralization are reflected (Fig. 1); 4) compile maps of computer evaluation of the prospects for finding ores in different variants using criteria given on a geological map, on geophysical maps, on a space photogeological map and using a complex of geological, geophysical and space photogeological criteria (Fig. 2 shows fragments of two such maps).

Tables 1 and 2 show that the information contained on a space photogeological map in its significance is commensurable with the information given on geological maps of this same scale. The high information content of the photometric and other characteristics directly present on the space photographs is affording possibilities for their further use in predictions even in poorly studied regions where geological-geophysical interpretation is difficult.

Table 2

Comparison of Effectiveness of Space Photogeological, Geological and Geophysical Criteria Used in Evaluating Prospects of Mineralization

Criteria	Informational significance, %	Maxima of information content of gradations, %
Space photogeological	42.5	36.7
Geological	40.4	39.2
Geophysical	17.1	24.1
	100.0	100.0

Table 3

Comparison of Results of Classification of Territory Using Criterion of Similarity to Reference Features

Similarity measure	Area, %		
	using geological criteria	using geological and space photogeological criteria	using geological, space photogeological and geophysical criteria
Over 0.75	18.4	6.4	4.3
0.55-0.75	3.8	9.0	7.2
0.25-0.55	45.4	43.9	25.3
Less than 0.25	32.4	40.7	63.2
	100.0	100.0	100.0

The low informational significance of some criteria, in the generally accepted opinion favorable for mineralization (presence of hydrothermally modified rocks, increased fissuring, presence of Mesozoic intrusions, with which mineralization in this region is associated), is attributable to the scale of the used materials and the detail of the forecast (prediction). Without question, with the use of large-scale maps and prediction of ore fields or deposits the presence of hydrothermal changes will play a greater role; in this case the possibility of using direct search criteria is not excluded. The reason for such a low information content of the other two mentioned factors is the high background value of the density of fissures (dislocations) and the widespread occurrence of Mesozoic intrusions. This reduces their usefulness in prediction and reconnaissance, which is taken into account by the algorithm; they can play an important role under the condition of a more detailed description or in the case of small-scale prediction (at the level of large ore zones). In general, the informational significance of any criterion is a variable value and is dependent on the scale of the investigations, the level of the prediction and the type of feature to be predicted.

The use of space photogeological maps made possible a threefold reduction in the area of the most promising sectors having a measure of similarity to the standard reference features above 0.75 (Table 3). At the same time, the fraction of areas having a minimum similarity to the reference features is increased by a third. Thus, the contrast of the evaluation of areas when using space photogeological maps jointly with a geological map increases substantially, which facilitates their interpretation. The use of geophysical information still further increases this contrast. We note that the reliability of classification of a territory with respect to prospects for mineralization does not deteriorate.

In evaluating the quality of classification of a territory use was made of standard control features -- ore regions, whose characteristics were not taken into account in formulating a decision rule for classification and formulation of an optimum model of an ore region. Among the 10 control features there was incorrect classification of only one, evaluated by a measure of similarity to the reference features less than 0.6. Such results seem entirely satisfactory.

Figure 2 shows that the defined most promising areas for the most part adjoin known ore regions. Within the limits of these areas there are known to be individual deposits and ore shows. In addition, new promising areas have been detected at a considerable distance from the earlier known regions, where only a few ore shows are noted on occasion. All the promising areas are characterized by a closeness to annular structures, associated with processes of Mesozoic intrusive and extrusive magmatism. They are situated near outcrops of Mesozoic extrusives and were localized amidst sedimentary rocks of the Upper Precambrian, metamorphized under conditions of epidote-amphibolite facies. A closeness to sublatitudinal regional faults is noted, as well as the presence of unexposed masses of granitoids within the limits of these areas. Promising areas usually have specific photocharacteristics.

It should be emphasized that the evaluations made are specialized for a specific region and type of mineralization. They cannot be applied to territories with other geological-geophysical and landscape-climatic characteristics and make it possible to predict features only of those classes which were used as references.

Conclusions. It was established that in an evaluation of one of the regions in the Far East, made using a computer, that the informational significance of space photogeological criteria is commensurable to the significance of the information present on geological maps of this same scale. In most cases the space photogeological information does not duplicate the already known geological information but contains fundamentally new information. The use of this information, together with that extracted from geological and also geophysical maps of the same scale, made possible a substantial reduction in the area of the most promising sectors with a simultaneous increase in the contrast of evaluations and retention of reliability of the evaluation.

Thus, space photogeological information in general and a space photogeological map in particular can be used in predictive-mineragenetic investigations. The proosed approach to complex use of geological, geophysical and space photogeological information will make it possible to carry out a purposeful synthesis of different types of information in a single index with allowance for the individual significance of each of the characteristics.

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ORBITAL PARAMETERS AND SENSORS OF A SYSTEM FOR STUDY OF THE EARTH'S NATURAL RESOURCES

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[Article by N. S. Ramm, A. M. Kuzina and I. G. Mal'tseva, Aerial Methods Laboratory, All-Union Scientific-Production Combine "Aerogeologiya," Leningrad]

[Text] Satellites for study of the earth's natural resources are artificial earth satellites specially intended for a multiple, rigorously periodic survey of the earth's entire surface over the course of one or more years with the routine transmission of information to ground reception stations. The operational systems for study of the earth's natural resources are the "Meteor" (USSR, [1]) and "Landsat" (United States, [2]). The use of their data is of an international character. Intensive work is being carried out for the improvement of these systems and the creation of new ones.

It has been established that the orbits of satellites for study of the earth's natural resources should be near-circular with an eccentricity $e \leqslant 0.003$, solar-synchronous (SS), have an altitude H from 400-500 to 1,000 km, and their trajectories should cover the earth's surface with equally distant trajectories which in each of the survey periods should pass through one and the same terrain points [3-5]. For the sake of brevity orbits satisfying the totality of enumerated conditions will be called "isotrajectory" orbits. Now we will examine the specifics of these orbits, we will describe the totality of their parameters directly associated with the survey conditions and we will derive the expressions required for ballistic computations, comparison and selection of variants of the systems.

Parameters and properties of isotrajectory orbits. We will assume that the following parameters of isotrajectory orbits are basic: P -- survey period, that is, the time interval (in days) between repetition of identical survey trajectories; m -- number of survey trajectories (trajectory passes), that is, the number of total revolutions of the satellite during the survey period; t_0 is the mean local time of a survey of points on the equator; T_0 is the moment (date and UT) of transit of the ascending node in the orbit in one of the satellite revolutions.

In addition to the main parameters, we will introduce the following parameters into consideration: n -- number of satellite revolutions per day, rounded off to the closest whole number;

$$\Delta = 2\pi R_{eq}/m \tag{1}$$

is the distance between adjacent points of intersection of survey trajectories with the equator, where R_{eq} is the earth's equatorial radius;

$$k = nP - m. \qquad (2)$$

First we will discuss the parameters P, m, n and k.

It is evident that

$$PT_s = mT, \qquad (3)$$

where T is the Draconian period of satellite revolution [5] and T_s is a time interval equal to the mean solar day. Since a satellite always passes through the ascending node of the isotrajectory orbit at one and the same local time, the corresponding Greenwich time is different for different trajectory revolutions, but constant for each survey period. Accordingly, P is the minimum whole number of days during which a satellite makes a whole number of revolutions. Taking into account the equalities (3) and (2), this means that m and k are numbers relatively prime with P and k = 0 only with m = n and P = 1.

In accordance with formulas (2) and (3)

$$k=m(nT-T_c)/T_c=P(nT-T_c)/T \qquad (4)$$

or

$$m:T_c=P:T=k:(nT-T_c), \qquad (5)$$

[c = s = solar] and by the definition of n the inequality $|nT - T_s| \leqslant 0.5T$ is correct. This makes it possible to formulate the following properties of the considered parameters:

1. $k > 0$, if $nT > T_s$, that is, if the satellite makes less than n full revolutions per day, and $k < 0$ in the opposite case.

2. k and m satisfy the restrictions

$$-0{,}5P \leqslant k \leqslant 0{,}5P, \qquad (6)$$

$$0{,}5P(2n-1) < m < 0{,}5P(2n+1), \qquad (7)$$

and an equality in formula (6) is attained only when $|k| = 1$, P = 2.

3. The n parameter can assume only two values 14 and 15 since only with 13.5-15.5 revolutions per day does the altitude of a SS orbit fall in the range 400-1,000 km [5]. This makes it possible, in particular, to write the restrictions (7) in the form

$$13{,}5P < m < 15{,}5P. \qquad (8)$$

4. The parameters m, P and k can be interpreted as the number of survey routes or zones overlapping respectively the earth's entire equator and its arcs on which the equatorial points rotate relative to the line of orbital nodes during the period T of satellite revolution and during the time interval $|nT - T_s|$. In other words, between survey trajectories for successive satellite revolutions there there are also P - 1 trajectories, and between trajectories registered after n revolutions -- $|k| - 1$ others (see Fig. 1, where P = 5, k = -2).

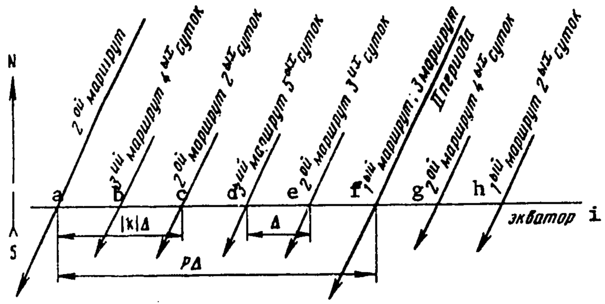

Fig. 1. Diagram of positioning of trajectories (P = 5, k = -2).

KEY:
- a. 2d trajectory
- b. 3d trajectory, 4th day
- c. 2d trajectory, 2d day
- d. 3d trajectory, 5th day
- e. 2d trajectory, 3d day
- f. 1st trajectory, 3d trajectory of period II
- g. 2d trajectory, 4th day
- h. 1st trajectory, 2d day
- i. equator

It follows from the latter property that with $|k|>1$ there can be a parallel survey carried out with a sensor with a large angle of view and covering the earth with the interval $|k|\Delta$ during the period

$$P_k=[P/|k|]+1, \tag{9}$$

where $[P/|k|]$ is the whole part of the number $P/|k|$. In this case adjacent trajectories of such a survey are registered on successive days and each P_k-th of them has an excessive overlap with one of the adjoining ones.

For isotrajectory orbits we will express the ordinary elements of the circular orbit -- mean altitude H and inclination i -- through the parameters P and m. For this purpose we use the formulas

$$T=2\pi\mu^{-1/2}p^{3/2}[1+\varepsilon\mu^{-1}p^{-2}(1-4\cos^2 i)+1{,}5e^2], \tag{10}$$

$$\delta\Omega=-2\pi\varepsilon\mu^{-1}p^{-2}\cos i(1-{}^2/_3\varepsilon\mu^{-1}p^{-2})-5{,}40\pi\cos i J_4 R_e^4 p^{-4}, \tag{11}$$

where μ = 398 601 km^3/sec^2, $\varepsilon = 1.5R_{el}^2$ J_2 = $2.63333\cdot10^{10}$ km^5/sec^2, $J_4 = -1.593\cdot10^{-6}$ and $J_2 = 1.082628\cdot10^{-3}$ are constants of the earth's gravitational field, p and e are the ellipse parameter and orbital eccentricity, $\delta\Omega$ is orbital precession during one satellite revolution. Expression (10) was derived by transforming the corresponding formula of perturbed motion of an artificial earth satellite [5], taking into account the principal terms of the influence of the second harmonic of geopotential. In deriving expression (11) use was made of the rigorous formulas for secular perturbation of the orbit under the influence of the second harmonic of geopotential and the formulas for the main terms of secular perturbation from 4-8 zonal harmonics [6]. In the expression for $\delta\Omega$ derived in this way we then discarded terms not exceeding hundredths of a microradian when $e \leqslant 0.003$ and $i \approx 98°$. [In the considered H range the inclination of SS orbits in the considered H range is 97-99°.]

In order for the orbit to be SS, the $\delta\Omega$ value must be equal to the mean angle of the earth's revolution around the sun during the time T:

$$\delta\Omega = 2\pi T/T_y, \tag{12}$$

where T_y = 365.24220 T_s is the time interval in one tropical year. Replacing p in formulas (10) and (11) by the mean length of the satellite radius-vector $r = p(1 + 0.5e^2)$ and adding equations (3) and (12) to it, we obtain a system of equations for determining i and r in dependence on P and m:

$$\begin{gathered} T_c P/m = 2\pi\mu^{-1/2} r^{3/2}[1+\varepsilon\mu^{-1}r^{-2}(1-4\cos^2 i)+0{,}75e^2] \\ T_c P/m = -T_r \varepsilon\mu^{-1} r^{-2}\cos i(1-{}^2/_3\varepsilon\mu^{-1}r^{-2}+e^2)-5{,}40\pi\cos i J_4 R_e^4 r^{-4}. \end{gathered} \tag{13}$$

This system makes it possible to compute H and i for isotrajectory orbits with an accuracy to 0.5 km and 0.'5 respectively. A greater accuracy scarcely makes sense in the evaluation and planning of parameters until one knows the specific orbital parameters e and ω exerting an influence on its long-period perturbations. An analysis indicated that without a further loss of accuracy in equations (13) it is possible to replace the small terms varying slightly for isotrajectory orbits by their mean values. This leads to the solution

$$\begin{gathered} H = r - R = -6367{,}5 + 42\,205(P/m)^{2/3}, \\ \cos i = -74{,}050(P/m)^{7/3}, \end{gathered} \tag{14}$$

where R = 6367.5 km is the earth's mean radius and H is expressed in kilometers. Thus, for each survey period P there are only several isotrajectory orbits for which the H and i values are determined by formulas (14) with the substitution into them of the numbers m relatively prime with P and satisfying the inequalities (8). Accordingly, with an accuracy to the choice of the moments t_0 and T_0 the set of isotrajectory orbits is a single-parameter family whose parameter P/m can assume all rational values in the interval (2/31, 2/27), determined by the restrictions (8). It goes without saying that this family is determined also by the stipulation of H or i, but the orbit corresponding to their arbitrary value is not, generally speaking, an isotrajectory orbit. The m, n, k, Δ, H and i values for a number of isotrajectory orbits are given in the table. The problems involved in the rational choice of the parameters P and m or parameters equivalent to them will be discussed after determining their relationship to the characteristics of the information sensors.

The striving to increase the routineness of operation of systems of satellites for study of the earth's resources and at the same time carry out a survey with a high resolution in the field led to proposals for including in the system M satellites for study of the earth's natural resources, supplying photographs with identical properties. From the above-formulated properties of the parameters P, m and k we have the following set of conditions necessary and adequate for reducing the total period of the survey to $P_M \approx P/M$ in this way: a) the P/M number -ust be whole; b) the orbital parameters P, M and t_0 of all satellites must coincide; c) the phase differences ΔT_0 of adjacent satellites must coincide: $\Delta T_0 = T/M$. With adherence to the enumerated conditions P_M is precisely equal to P/M. A survey with $|k|>1$ and $M>1$ is most rational, provided that P_k/M is a whole number. When this is so, the total period of the additional survey is $P_{Mk} = P_k/M$. In remaining cases $P_{Mk} = [P_k/M] + 1$.

Orbital Parameters and Survey Parameters Promising for Systems for Study of Earth's Natural Resources

P, сутки a	16				18		20	
n	14		15		14	15	14	15
k	—3	—5	5	3	—5	5	—3	3
m	227	229	235	237	257	265	283	297
H, км b	834	792	670	630	804	659	847	618
i	98°44′	98°34′	98°04′	97°54′	98°37′	98°01′	98°48′	97°51′
D, км	194	192	188	186	171	186	156	148
$2\beta°$	13,2	13,8	15,9	16,8	12,2	14,4	10,5	13,7
d, м	51	51	50	49	46	44	41	39
ν	1,016	1,018	1,023	1,025	1,013	1,018	1,010	1,016
$\lvert\varphi°\rvert_{max}$	82,1	82,3	82,8	82,9	82,2	82,7	81,9	82,8
D_k, км	581	961	938	558	856	832	466	446
$2\beta_k°$	38,0	61,3	68,6	47,4	55,2	63,6	30,6	39,4
d_k, м	148	226	214	139	206	195	121	113
ν_k	1,15	1,45	1,59	1,23	1,26	1,36	1,09	1,43
$\nu_k d_k$, м	170	328	339	171	259	266	132	162
$\lvert\psi_k°\rvert_{max}$	83,9	85,7	86,1	84,7	85,2	85,8	83,4	84,2
P_k, сутки b	6	4	4	6	4	4	7	7
P_{2k}, сутки	3	2	2	3	2	2	4	4
$D_{P/2}$, км	1550	1538	1501	1489	1542	1498	1555	1485
$2\beta_{P/2}°$	82,5	84,9	92,7	95,6	84,2	93,5	81,9	96,5
$d_{P/2}$, м c	320	313	289	280	315	287	323	278
$\nu_{P/2}$	2,11	2,20	2,57	2,74	2,18	2,62	2,08	2,80
$\nu_{P/2} d_{P/2}$, м	675	687	743	767	687	752	672	778
$\lvert\psi_{P/2}°\rvert_{max}$	88,2	88,4	88,7	88,8	88,3	88,7	88,2	88,8
d_P, км	3100	3077	3002	2978	3083	2995	3110	2970
$2\beta_P°$	112,7	114,7	120,7	122,9	114,1	121,3	112,1	123,5
d_P, м	438	423	376	360	427	372	442	355
ν_P	6,56	7,08	9,19	10,20	6,92	9,44	6,42	10,53
$\nu_P d_P$, м	2873	2095	3455	3672	2955	3512	2838	3738

KEY:
- a) days
- b) km
- c) m

Now we will proceed to an examination of the parameter t_0 determining at what local time, that is, at what solar altitude $h_\odot$, the survey is made. The parameter t_0 is related to the right ascensions $\alpha_\odot$ and Ω of the sun and the ascending node of the orbit by the dependences

$$\Omega=\alpha_\odot+t_0-12^h; \quad \Omega=\alpha_\odot+t_0. \tag{15}$$

The first of the expressions indicated in (15) corresponds to a survey on the ascending and the second corresponds to a survey on the descending revolutions of the orbit. We note that the combination of formulas (14) and (15) determines all the elements of the computed circular isotrajectory orbit, that is, H, i, Ω and T_0, through its parameters P, m, t_0 and T_0. T_0 in this case, together with t_0, fixes the longitude of the point of intersection of one of the survey trajectories with the equator and thereby determines the position of all the trajectories on the earth's surface and the date of surveying of each of them.

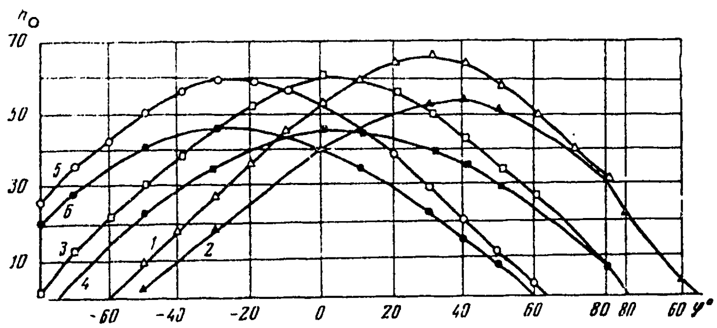

Fig. 2. Solar altitude in degrees at time of survey in dependence on local latitude. The right edge of the graph corresponds to an additional survey of the latitudes 60-80° on the ascending branch of the orbit. 1) survey of 22 June, t_0 = 1000 hours; 2) t_0 = 0900 hours; 3) 21 March or 23 September, t_0 = 1000 hours; 4) t_0 = 0900 hours; 5) 22 December, t_0 = 1000 hours; 6) t_0 = 0900 hours.

The difference $\Delta t = t - t_0$ is the local mean time of survey of points situated at the latitude φ and at the equator, equal to the difference $\Delta\lambda$ of the right ascensions of the satellite at the times of passage through the corresponding orbital points. According to [5], $\sin \Delta\lambda = \pm \mathrm{tg}\,\varphi/\mathrm{tg}\, i$. Accordingly,

$$t=t_0+\Delta t=t_0\pm \arcsin(\mathrm{tg}\,\varphi/\mathrm{tg}\,i)\,T_c/2\pi, \tag{16}$$

the "+" sign corresponds to a survey on the ascending orbital branch and "-" corresponds to a survey on the descending orbital branch. The conversion from local time t to solar altitude $h_\odot$ at this time is accomplished using the ordinary formula

$$\sin h_\odot=\sin\varphi\sin\delta_\odot-\cos\varphi\cos\delta_\odot\cos t. \tag{17}$$

Computations by the cited formulas show that the best illumination conditions for the entire earth, other than Antarctica and the ocean areas adjacent to it, are obtained in a survey on the descending branch of the orbit in the morning hours with $t_0 \approx 0930$ hours or on the ascending branch in the evening hours with $t_0 \approx 1430$ hours. Figure 2 shows curves of $h_\odot$ values for a survey on the descending branches with t_0 equal to 1000 and 0900 hours on the dates of the solstices and equinoxes. These same curves are true for a survey on the ascending branches with t_0 equal to 1400 and 1500 hours respectively. The figure shows that the t_0 values in the interval 0930-1000 hours are actually optimum: with larger t_0 there is a rapid increase in $h_\odot$ of a survey in the tropical regions, whereas with lesser t_0 there is an unjustifiable deterioration in illumination conditions in the high latitudes of the southern hemisphere. It follows from formulas (16) and (14) that with $|\varphi| \geqslant 70°$ the time t is highly dependent on orbital altitude H. However, the $h_{\odot}$ values vary with a change in H from 600 to 900 km by not more than 1-2°, that is, Fig. 2 is suitable for all isotrajectory orbits.

It follows from Fig. 2 that there is a possibility for an additional survey of the arctic regions during the spring-summer months during the time of transit of the satellite through the northern part of the ascending branch of the orbit with a solar azimuth approximately 90° greater than is usual for the system. The accomplishment of such a survey, broadening the possibilities of photometric methods for interpretation, requires the stipulation of $t_0 \approx 0900$ hours and the additional activation of sensors for several minutes with each satellite revolution.

Dependence between parameters of isotrajectory orbits, parameters of sensors and survey characteristics. Now we will proceed to an examination of the principal, from the point of view of the user, characteristics of the survey, that is, the resolution in the terrain d; covered zone (width of the terrain zone registered along each trajectory) D; angle of field of view of sensor 2β; coefficient of image compression toward the edges of the intercepted zone ν; fractions of overlap g and g_{φ} of intercepted bands at the equator and at the latitude φ; flow of information I received in a survey in a unit time.

For a more definite presentation we will assume that the sensor is a scanning device with the following invariable parameters: δ is the instantaneous angle of the field of view; N is the number of elements in the line; q is the fraction of overlapping of adjacent elements of the line; ϑ is the time interval between the registry of adjacent line elements; l is the number of simultaneously registered lines; τ is the scanning period, the time interval between the registry of identical elements of the j-th and $(l+j)$-th lines.

We will assume that d is a resolution element at the nadir (at the center of the photograph line). In addition, we introduce the resolution elements d_0 and d_β along the line, at its center and at its edge respectively. We will bear in mind that the stipulated overlap between adjacent survey lines is zero and the coefficients

$$1-g\approx0{,}9;\ 1-q=0{,}25;\ c=\tau/N\vartheta\approx1{,}5 \tag{18}$$

vary in a small range. Accordingly, it is easy to see,

$$d=H\delta,\ d_0=(1-q)\,d,\ d_\beta/d_0=\nu, \tag{19}$$

$$2\beta=N(1-q)\,\delta=(1-q)\,Nd/H, \tag{20}$$

$$D=\Delta\sin i/(1-g)=2\pi R_э\sin i/(1-g)\,m\approx c_1/m\approx c_2/P=30\cdot10^2\ \text{км}/P, \tag{21}$$

$$\tau=Tld/2\pi R=T_cPld/2\pi Rm\approx c_3ld, \tag{22}$$

$$\vartheta=\tau/cN=T_cPld/2\pi RcmN\approx c_4ld/N=0{,}15\cdot10^{-4}ld/N, \tag{23}$$

where $c_1, \ldots, c_4$ (like the c_5–c_{10} introduced below) are proportionality factors. The approximate equalities in formulas (21)-(23) are based on the restrictions (8), according to which

$$m\approx14{,}5P. \tag{24}$$

For practical purposes, as will be indicated below, formula (24) determines m with an accuracy to 2%.

In order to determine the dependence of β and d_β on D we will use Fig. 3, representing the instantaneous scanning plane passing (with an ideal orientation of the optical axis of the sensor on the center of the earth) through the sensor S, the center of the earth O and the terrain points M and Q, registered at the edge and at the center of a photograph line respectively. It follows from the figure that:

$$\frac{\sin\beta}{\sin(D/2R)}=\frac{R}{\overline{MS}}=\frac{R\cos\beta}{H+R-R\cos(D/2R)}.$$

$$d_\beta=\overline{MM'}=\overline{MM''}\sec(\beta+D/2R)=(\overline{MS}/R)R(1-q)\delta\sec(\beta+D/2R).$$

Accordingly,

$$\operatorname{tg}\beta=R\sin(D/2R)/[H+R-R\cos(D/2R)], \tag{25}$$

$$d_\beta=\nu d_0=d_0R/H\sin(D/2R)\csc\beta\sec(\beta+D/2R). \tag{26}$$

The last equations can be replaced by the more graphic approximate formulas:

$$2\beta\approx D/H(1-0{,}08D^2/H^2), \tag{27}$$

$$\nu\approx\sec^2\beta(1+0{,}4D^2/RH). \tag{28}$$

Formula (27) ensures an accuracy to 1% when $2\beta<65°$, formula (28) -- when $2\beta<80°$.

The overlap g_φ between the interception zones at the latitude φ is determined from the obvious equation: $D(1-g_\varphi)\sec A_\varphi = 2\pi R_{el}\cos\varphi/m$, where A_φ is the azimuth of the trajectory of the satellite for study of the earth's resources at the latitude φ. Taking into account formulas (1), (21) and that $\sin A_\varphi = \cos i\sec\varphi$ [5], we have

$$1-g_\varphi=(1-g)\csc i(\cos^2\varphi-\cos^2 i)^{1/2}. \tag{29}$$

It follows from this formula that with $|\varphi|$ 55° the overlap g_φ attains 50% and the zone of continuous triple overlap begins with $|\varphi|\approx 67°$.

The information Mbit/sec supplied each second by a satellite for study of the earth's natural resources during a survey with a sensor with the parameters τ, l, N is expressed by the formula

$$I=c_5c_6c_7lN/\tau=2\pi Rc_5c_6c_7mN/T_cPd, \tag{30}$$

where c_5 is the number of spectral channels of the sensor, 2^{c_6} is the number of gradations describing the brightness of each element, c_7 is a coefficient dependent on the volume of the calibration data, service information, code excess, etc. Assuming $c_5 = 4$, $c_6 = 6$ and $c_7 \approx 2.5$ and taking into account equality (24), we obtain

$$I\approx c_8N/d\approx 0{,}4N/d, \tag{31}$$

where d is expressed in meters.

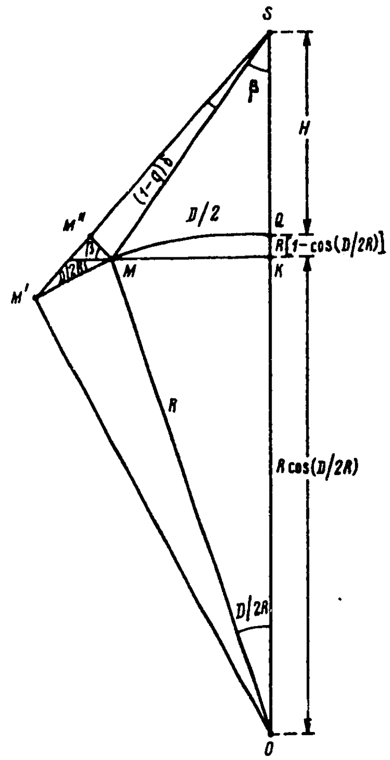

Fig. 3. Diagram used in derivation of dependence of β and d_β on D.

Finally, we note that for scanning devices the role of exposure is played by the η value, proportional to ϑ and δ^2. According to formulas (19) and (23) it can be written in the form

$$\eta \approx c_3 l d^3/NH^2. \tag{32}$$

According to existing concepts [7, 8], the orbit and sensor of the satellite for study of the earth's natural resources should ensure a survey of a high or superhigh resolution in the visible and near-IR spectral ranges with d = 30-60 m. At the same time it is desirable to make a survey with a resolution element 100-250 m and a substantially lesser period (routine survey with a medium resolution). The installation of an additional small-resolution sensor with a scanning period of one day and the simultaneous use of two satellites is also not excluded. According to the material presented above, this means that the survey period P must be even and $|k| = |nP - m| = 3$-5.

The creation of sensors with a high and superhigh resolution for systems of satellites for study of the earth's natural resources involves a number of difficulties impeding an unlimited decrease in d and imposing additional restrictions on the parameters P and m. We will examine the most important of these. First of all, it follows from formula (27) or (25) that $2\beta H > D/2$ or, taking formulas (20), (21) and (18) into account,

$$PNd > 2 \cdot 10^6 \text{ м}. \qquad (33)$$

Since in the foreseeable future it is difficult to expect the appearance of sensors with $N > 5000$–7000, this means that for systems with high and superhigh resolution $P > 5$. It can be demonstrated that this makes it possible to replace the inequality (33) for such systems by the approximate equality

$$PNd \approx 2{,}7 \cdot 10^6 \text{ м}/(1-g)(1-q) = c_{10} = 4{,}0 \cdot 10^6 \text{ м}, \qquad (34)$$

whose left-hand side is correct with $N < 7000$ and $d < 60$ m with an accuracy to 4–5%.

In formulas (23), (31) and (32) replacing N by c_{10}/Pd, from them and from formulas (19) and (34) we obtain the following set of equations correct for sensors with a high and superhigh resolution:

$$d = H\delta \approx c_{10}/PN \approx (c_{10}/c_4)^{1/2}\vartheta^{1/2}/l^{1/2}P^{1/2} \approx (c_8 c_{10})^{1/2}/I^{1/2}P^{1/2} \approx$$
$$\approx (c_{10}/c_9)^{1/4}H^{1/2}\eta^{1/4}/l^{1/4}P^{1/4}. \qquad (35)$$

In each period of time the set of technical possibilities and economic considerations limits the δ, ϑ, η and N, l, I values to some limiting values δ_{min}, ϑ_{min}, η_{min} and N_{max}, l_{max}, I_{max}. This makes it possible to draw the following conclusions from equations (35):

1. In order to increase the resolution (that is, decrease d), insofar as possible it is necessary to decrease H and increase P.

2. By decreasing d due to an increase in P with fixed (limiting) values of the remaining parameters, it is possible to arrive at a moment when the really limiting factor is the first of equations (35) or the last of them, also represented in the form

$$\eta \approx c_9 c_{10}^3 l/(H^2 N^4 P^3). \qquad (36)$$

A further increase in P in any reasonable limits for all practical purposes does not lead to a decrease in d. According to formula (36), a multiple increase in N, even if it is in itself technically possible, results in a reduction in P and in the last analysis to an increase in d.

3. With fixed P, H and l a decrease in d by a factor of 2 corresponds to an increase in the flow of information by a factor of 4, a decrease in the time required for the registry of a point by a factor of 4 and a decrease in the exposure by a factor of 16.

4. Systems with a high resolution inevitably have a large survey period, that is, are not very "operational," having a small interception zone and insignificant compression of the lines toward the edges.

With a decrease in H there is a decrease in the stability of an isotrajectory orbit and its corrections are complicated, but the increasing information on the earth's gravitational field and the properties of the upper layers of the atmosphere facilitates the overcoming of these difficulties. Accordingly, even now the creation of systems with H = 900 km is scarcely feasible. With $|k| = 3\text{-}5$ this means that for each P it is rational to use only two orbits: with n = 14, $k<0$, H = 760-840 km and with n = 15, $k>0$, H = 620-700 km. The above-mentioned accuracy of formula (24) specifically corresponds to such orbits. Thereafter a conversion to the parameters n = 15, $k<0$, H = 460-540 km is not precluded, but it is quite complex.

The "Landsat" system, for which d = 79 m, N = 3230, P = 18, H = 918 km, was already created eight years ago. The planned foreign systems of satellites for study of the earth's natural resources are intended for a period of this same order of magnitude. A decrease in d evidently is to be achieved by progress in the designing of sensors, a decrease in H, an increase in ℓ and a decrease in the parameters g, q and c approximately to values corresponding to the formulas (18).

With $14<P<22$ there are only eight isotrajectory orbits with even P, $|k| = 3\text{-}5$, H = 500-900 km. The parameters of all these orbits, being most promising for systems of satellites for study of the earth's natural resources, and also the corresponding survey parameters, are summarized in the table. In this table $|\varphi^\circ|_{max}$ denotes the modulus of the latitude of the earth's extreme parallels registered by the system; the subscript k denotes parameters relating to a sensor simultaneously registering $|k|$ zones on the ground with the width D and making a survey with the period P_k days, and when using two satellites -- with the period P_{2k} days; the subscripts P and P/2 designate parameters relating to sensors taking in at once P or P/2 zones. The first of these ensures scanning of the entire earth in the course of 24 hours from one artificial earth satellite, the second -- from two artificial earth satellites. In the table for all sensors it was assumed that g = 0.10, q = 0.25, N = 5000.

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